Harmonization of new wind turbine rotor blades development process: A review

B. Rašuo *, M. Dinulović, A. Veg, A. Grbović, A. Bengin

University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

ABSTRACT

In this paper the harmonization of new wind turbine rotor blades development is given as well as the analysis of behavior by verification testing for a wind turbine rotor blade of composite materials. The design, fabrication, the status of wind energy standards and the analysis of behavior by full-scale verification testing for wind turbine rotor blades of composite laminated materials is given, too. The experimental methodology of static, vibratory and fatigue tests for the wind turbine rotor blade of composite laminated materials is presented. These verification tests were performed after the rotor blade development had been completed. The development of the rotor blade was performed using the PC computer with the CATIA designing system and the Gerber Garment cutter system. The blade was fabricated from composite laminated materials. The contour of airfoil was formed by a continuous structural pocket and a fiberglass skin.

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Contents

1. Introduction

High strength and stiffness, low density, and good fatigue and corrosion resistance, all are properties that make high-performance composites appropriate for numerous wind energy and aerospace applications. Fiber-reinforced composites are increasingly used in critical structures in wind energy. However, many problems have arisen from introducing these materials, such as the development of entirely new design, fabrication, and qualification discipline,

difficulties in analyzing internal stresses, demonstrating this technology to certifying agencies, determination of adequate test criteria, and quantifying environmental degradation.

The active coordination and harmonization of all processes on the relation: design (aerodynamical improvement etc.), regulations and standards, manufacturing, materials and technology, and verification testing are presented in Fig. 1.

The most important issue in developing new wind turbine rotor blades is the application of contemporary technology solutions in the designing and manufacturing process. In the paper [1], along with the progress of modern wind energy technology, the trends of wind energy technology and potential challenges have been thoroughly studied. The wind-energy technology is established itself but

not yet fully mature and hence there are many areas where improvements are required to reduce the cost of wind energy. The book of science and technology [2] provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Other, very significant elements for the development of technologies for manufacturing the new wind turbine can be found in the International Energy Agency publication [3].

The increase of the efficiency and working envelope of wind turbine implies increasing application of adaptive blades, morphing technologies and smart structures. Morphing technologies are currently, receiving significant interest from the wind turbine community because of their potential high aerodynamic efficiency, simple construction and low weight [4]. Morphing structures are good candidates for wind turbine flaps, because they have the potential to create structures that have the conflicting abilities of load carrying, lightweight and shape adaptive [5]. The paper [6] focuses on research of active rotor control and smart structures for load reduction. It presents an overview of available knowledge and future concepts on the application of active aerodynamic control and smart structures for wind turbine applications. The goal of the paper is to provide a perspective on the current status and future directions of the specific area of research. Other very interesting and innovative ideas on adaptive constructions can be found in the

Expert Meeting proceedings held at Sandia National Labs, Aluquerque, USA, May 2008 [7].

The important issue on the safety and reliability of wind turbine operation is an experimental verification of wind turbine blades in full-scale. Since the blades are one of the most critical components of a wind turbine, representative samples must be experimentally tested in order to ensure that the actual performance of the blades is consistent with their specifications. In particular, it must be demonstrated that the blade can withstand both the ultimate loads and the fatigue loads to which the blade is expected to be subjected during its design service life [8]. In the paper [9], a review of full-scale structural testing of wind turbine blades is presented. Other details concerning the advanced blade testing methods for wind turbines can be found in the M.S. Thesis from the University of Massachusetts [10].

A full-scale test approach independent of the design process must be given prominence in the procedure of wind turbine components and system development and qualification [11]. A fatigue program, including the static and vibratory tests, stress surveys and coupon or subelement programs, is conducted for the case of fatigue-loaded wind-critical components [12].

The importance of full-scale testing in the development (and/or redesign) process for fiber-reinforced composite wind turbine blades is discussed, and illustrated by means of an example drawn from Aeronautical Department (Faculty of Mechanical Engineering, University of Belgrade) experience in the use of composites in a wide variety of structural applications [13]. The laboratory investigations of the structural properties are conducted at Aeronautical Department on all wind-critical dynamic components in order to determine structural adequacy in the designing process [14].
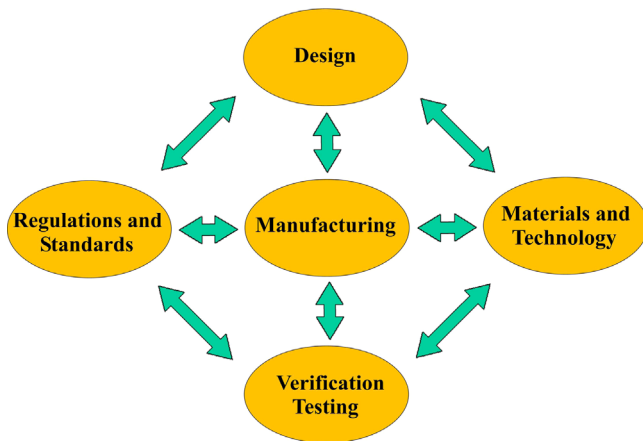
2. Status of wind energy standards

Continuous effort is required in the translation of research and development findings into updated standards and certification procedures. The first activities to establish standards and design certification procedures started in the early 1980s on a national scale in the countries like Denmark, the Netherlands and later in Germany. In the late 1980s and early 1990s, standardization activities were incorporated into international frameworks [15]. The International Electro-technical Committee (IEC), and CEN and CENELEC (1995) provide working platforms on a global and

Fig. 1. The harmonization of new wind turbine rotor blades development.

Table 1
The current status of wind turbine standardization area [15–22].

Design requirements	
Wind turbines	IEC 61400-1 (ed. 2 and ed. 3)
Small wind turbines	IEC 61400-2 (ed. 1 and ed. 2)
Offshore wind turbines	IEC 61440-3
Gear boxes for turbines from 40 kW to 2 MW and larger	ISO/IEC 81400-4
Requirements for measurements	
Acoustic noise measurement techniques	IEC 61400-11, ed. 2
Wind turbine power performance testing	IEC 61400-12, ed. 1
Power performance measurements of grid connected wind turbines	IEC 61400-12-1
Mechanical loads	IEC TS 61400-13, ed. 1
Declaration of apparent sound power level and tonality values	IEC TS 61400-14, ed. 1
Power quality characteristics of grid connected wind turbines	IEC 61400-21, ed. 1
Full-scale structural testing of rotor blades	IEC TS 61400-23, ed. 1
Other standardization area	
Lightning protection	IEC TR 61400-24, ed. 1
Communication for control and monitoring	IEC 61400-25
IEC system for conformity testing and certification of wind turbines	IEC WT 01, ed. 1
Protective measures	EN 50 308, ed. 1
Electromagnetic compatibility	prEN 50 373
Declaration of sound power level and tonality values	prEN 50 376
International electrotechnical vocabulary, Part 415	IEC 60050-415

Fig. 2. Automated Gerber-marker making system.

Fig. 3. Matched composite die.

European level, respectively. Reduction of uncertainties or risk, especially from the viewpoint of insurers and financiers of wind energy projects, requires highly reliable standards [16].

At present, implementation of certification of wind turbines or components is a must worldwide. In addition, certification to harmonized requirements is an active support of export. Hence, it is of importance for manufacturers, banks and insurances of wind turbines and components to be knowledgeable about different certification processes as well as guidelines [17,18]. The IEC WT 01: IEC System for Conformity Testing and Certification of Wind Turbines, Rules and Procedures, 2001 is used as a basis for describing the procedures to obtain the Type and Project Certificates [19]. Design Evaluation, Manufacturing Evaluation, Evaluation of Quality Management and Type Testing are comprised by the Type Certification. It is the foundation of the Project Certification that involves the aspects of Site Assessment, Foundation Design Evaluation and Installation Evaluation (optional) [20]. These individual modules are concluded with Statements of Compliance. It is only after the successful completion of the relevant Type Certification and Project Certification that certificates are issued [21]. The Committee of IEC has prepared a number of standards for wind energy and gives an overview of the publications as of mid 2005 [22]. The current status of wind turbine standardization is given in Table 1.

It is very interesting to compare the requirements for commercial aircraft and large wind turbines [23,24]. A comparison of FAR 25 (structural code for commercial aircraft), and IEC 61400-1 (structural code for large wind turbines) gives similar material allowable (characteristic strength) requirements [25,26]. Aircraft loads are also subjected to a safety factor of 1.5 compared with that of 1.35 for wind turbine blade aerodynamic loads, adding an additional margin for comparison [27–29].

3. Design and fabrication

There were four main steps, such as (1) blades design on the PC using CATIA designing system (Fig. 2), (2) preparation and cutting of blade components on the Gerber-Garment cutting system, (3) blade manufacturing in a two-section die (Figs. 3 and 4) final verification testing, in the development of wind turbine rotor blades (upwind rotor with active pitch control, gearless, variable speed, clockwise, rated power: 2 MW, rotor diameter: 82 m, swept area: 5281 m^2, specific rating: 0.380 kW m^{-2}, and hub height 100 m) [30].

Two different blades of wind generators with the same distribution along the span airfoil NACA 63 (2) 615 were designed for given conditions of power [31]. One classical blade (Figs. 4 and 5) and one with adaptive airfoil shape (Figs. 6 and 7), with an aim to achieve maximum energy performance for each energy potential wind turbines within the wind farm [32]. The aim was to start work possible wind turbine at the ground level of about 2 m/s wind speed [33].

Following the basic sense of adaptronic system to adapt its shape and structure of current external conditions, the idea was that the kinematic changes approximates elastic airfoil shape. At the current level of development this can be done when the airfoil is divided only into several rigid segments that move and necessary interdependent positions adjust blade optimum flow conditions that ensure maximum power efficiency of wind turbines. The final goal is to complete the farm for particular orography of the terrain (Fig. 8).

The design of two different types of wind turbines, the construction of which is derived using a software package CATIA, shows a full validity of the concept of adaptive blades in an attempt to make the most of the available wind energy potential, both at the farm level and for each individual wind turbine. Applying the concept of control of the boundary layer turbulence in the wake, the active control of shape and flow around the wind turbine fully confirmed safety requirements in terms of maximizing energy performance wind farm at the selected location.

After defining the optimum blade geometry by a multi-criteria analysis, which is based on the genetic optimization algorithm as a member of the Pareto front after 1800 generations, and designing the panelized wind turbine model in the software package CATIA turbine blades, the tower and nacelle of Direct-Drive type of wind
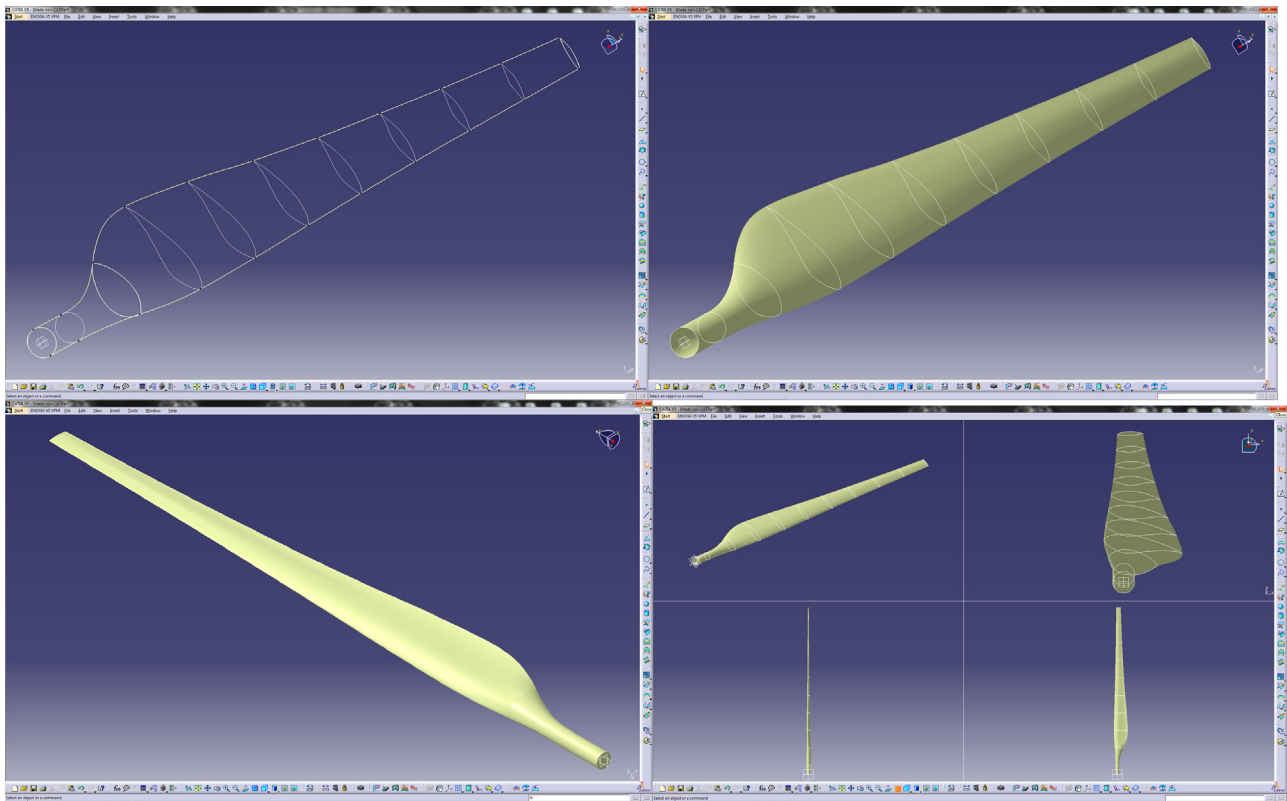
Fig. 4. Evaluative NACA 63 (2) 615 airfoils cross-sections (RISØ-R-1280 (EN) Wind Turbine Airfoil Catalogue [20]).
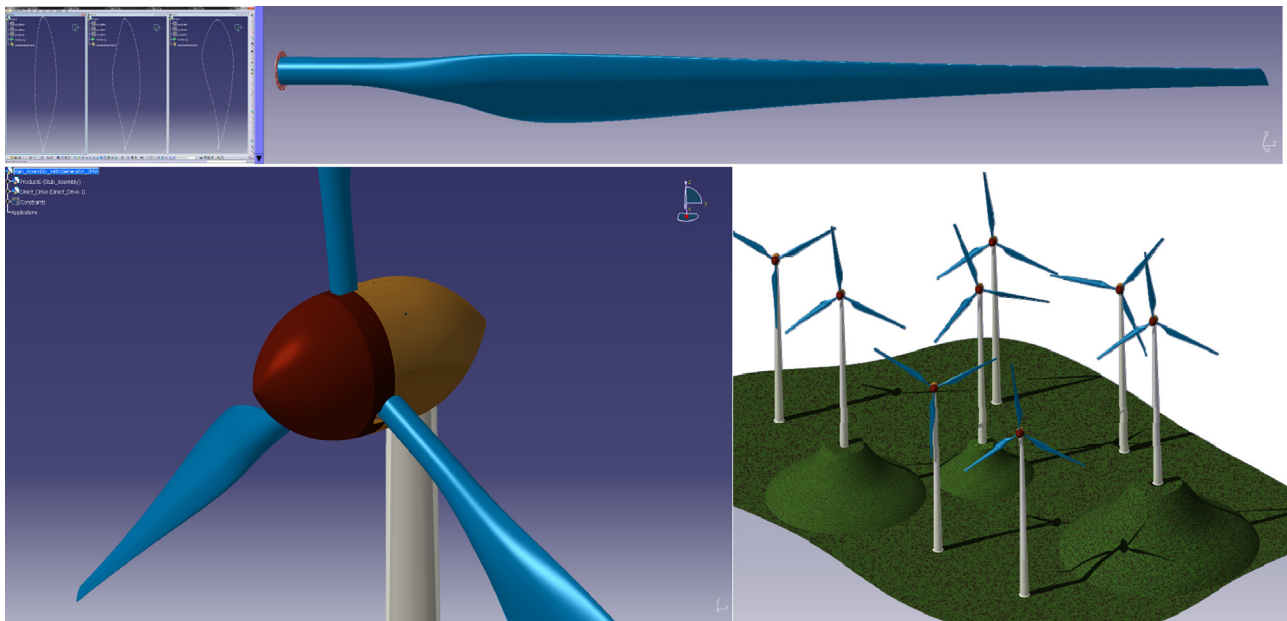

Fig. 5. (a) CATIA models shapes airfoils, (b) the final look of optimized wind turbine blade, (c) direct-drive type wind turbine of 2 MW, equipped with optimum shaped blades used for the nominal regime, (d) the designed wind farm type of direct-drive wind turbines.

turbine, and then the whole farm on the selected location (Fig. 5d and Fig. 8b) was done. More details can be found in Refs. [34–37].

In the blade manufacturing procedure the conventional composite materials with epoxy resin matrix, a fiberglass filament spar, a ten-section skin of laminated fabrics, some carbon filament embedded along the trailing edge and core were used. All used materials are standard products fabricated at Ciba-Geigy, Interglas

GmbH, Torayca, Brochier, Hexcel Composites and Clark-Schwebel International S.A [11–14].

Each blade consists of a fiberglass-epoxy spar and a fiberglass blade section which is fastened to the outboard end of the spar. Unidirectional fiberglass-epoxy is used to provide a high modulus in the axial direction and adequate torsional stiffness for full pitch change motion of the blade. Similarly, flapping (out-of-plane)
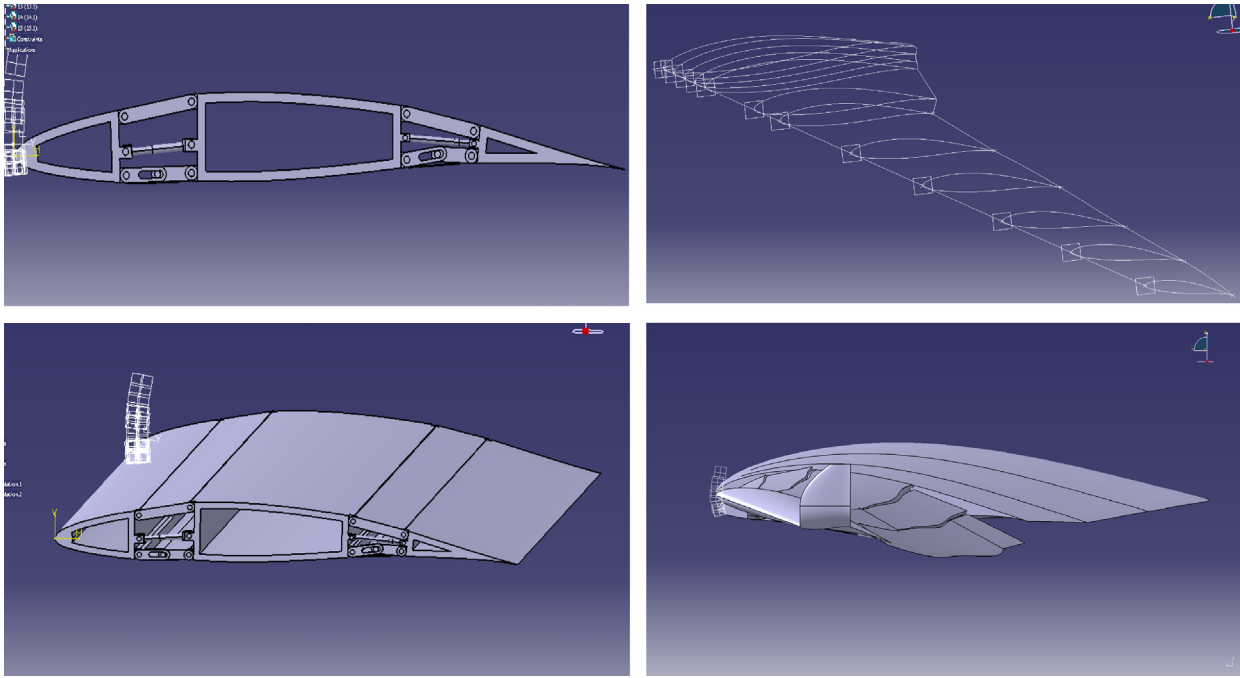
Fig. 6. (a) Change forms adaptive lifting surfaces, (b) design the characteristic airfoil sections for forming adaptive wind turbine blade, (c) segment of adaptive wind turbine blade, (d) adaptronic lifting surface of wind turbine blade.
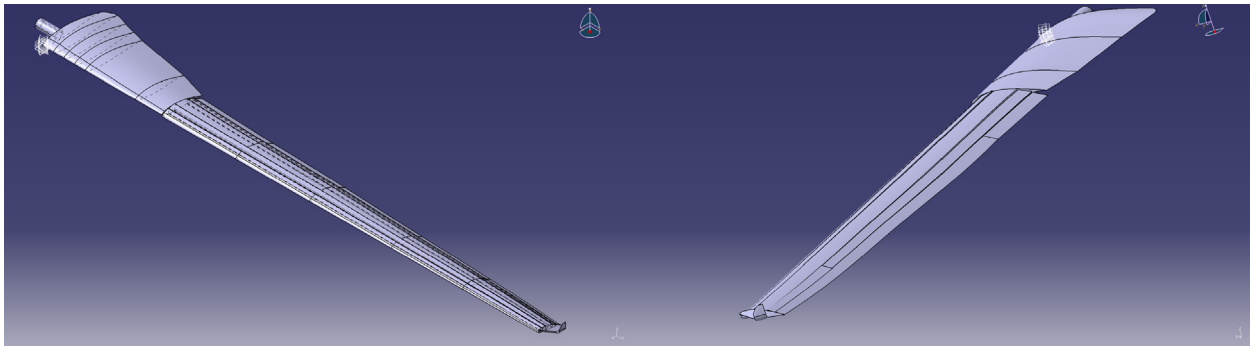

Fig. 7. (a) Adaptronic blade with characteristic NACA 63 (2) 615 airfoil sections, (b) adaptronic blade of wind turbine in the position of the maximum deviations slats and flaps—the view from the back of the blade.

motions are accommodated through elastic bending of the spar. The spar cross-section provides the high edgewise (in-plane) stiffness required for an aeroelastically stable rotor.

The inboard or torque tube portion of the blade is not supported by core and is designed to provide high torsional rigidity. The trailing edge contour of the airfoil is formed by a continuous structural pocket which has a fiberglass skin. The upper and lower skins are fabricated from woven fiberglass that is laid up with the fibers oriented at $\pm 45°$ and $0°/90°$ to the blade longitudinal axis. On the blades, the inplane blade natural frequency is tuned by stiffening the trailing edge of lower skin with some carbon filaments.

In the assembly, the first process is to cut the fiberglass fabrics to the required shape with mechanical knife and stacking it to build up the required shapes.

The next stage is wovenwrap and placing it in a matched composite tool, together with the fiberglass filament spar, uncured trailing edge skins and tool transferred to heated platten press (Fig. 3).

The resin (Ciba-Geigy Type) used in blade manufacture is cured in two stages. In the first stage, the component is warmed (70 °C to 90 °C, the duration of 2 h) until the resin becomes fluid. The matrix

is then consolidated and shaped by pressure. This reduces the bulk of the material and drives out included air. The component may then be fully cured by raising the temperature to 120 °C (1 h).

4. Verification testing

The verification test program for a wind turbine rotor blades encompassed static and dynamic testing (Following requirements for measurements: Full-scale Structural Testing of Rotor Blades—IEC TS 61400-23, ed. 1) [19].

The static tests of the blade involved experimental evaluation of torsional and flexional blade stiffness, elastic axis position of the rotor blade, verification of buckling stability, and failure beyond limit load is recommended but not required [38,39].

Dynamic tests involved the testing of vibratory characteristics and verification testing of blade fatigue properties. The aim of the rotor blade vibratory testing program was to determine the blade main aeroelastic properties [40,41]. The program included determination of the natural oscillation modes and the structure's natural frequency and also evaluation of blade structural damping [13]. The logarithmic decrement of the free vibrations was utilized to
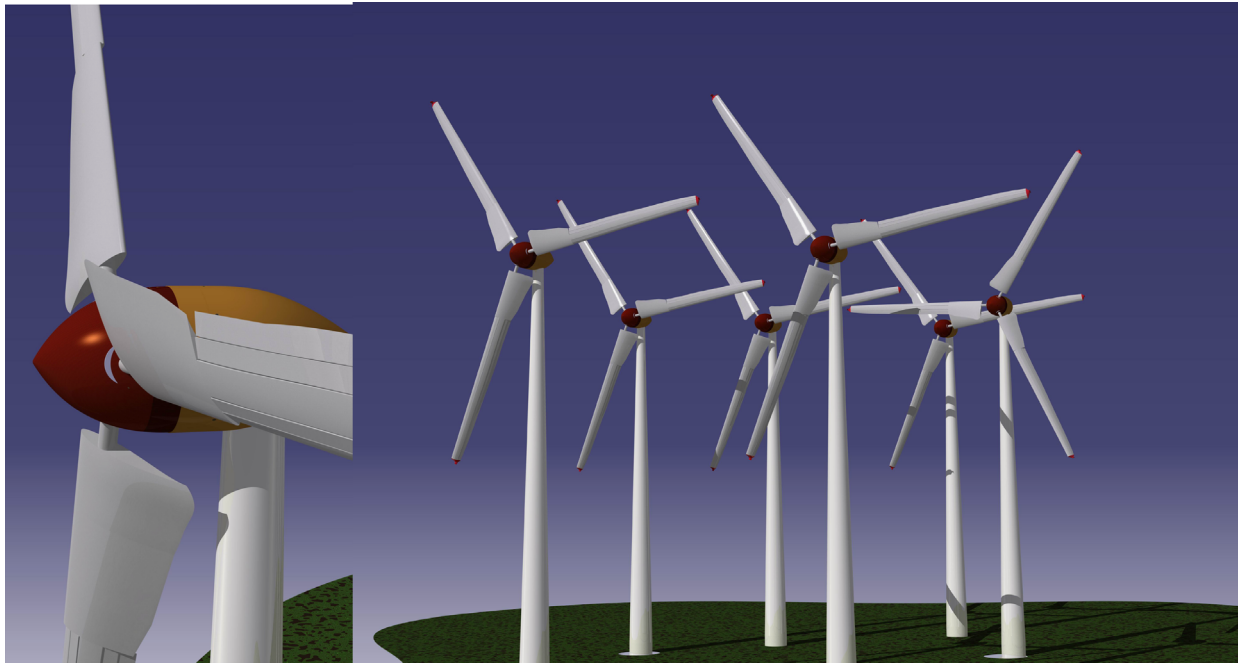
Fig. 8. (a) Direct- drive type wind turbine of 2 MW with adaptronic blade, (b) wind farm type Direct-drive of 2 MW with adaptronic blades.
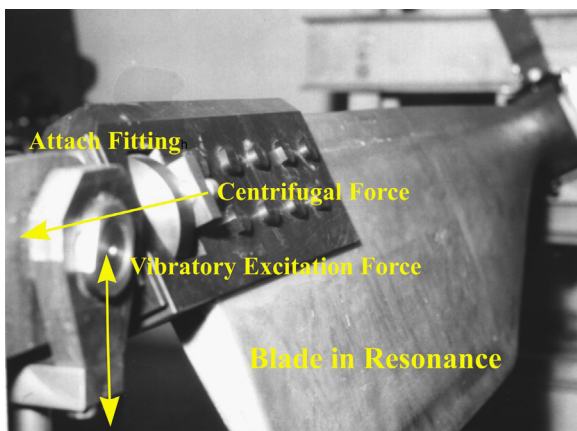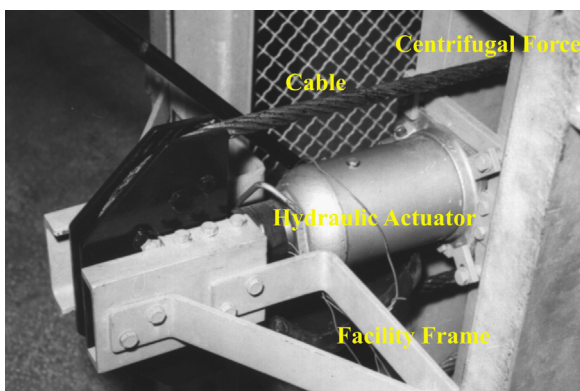

Fig. 9. Rotor blade in fatigue testing.

Fig. 10. The module for the centrifugal force simulation.

characterize the structural damping of blades. Q-factor is also commonly used to define the structural damping and gives relative energy reduce in successive oscillations [42,43].

The fatigue test program of the blade included: interlaminar separation (delamination) testing and geometric deformation of the blade cross-sections following the fatigue test program during which real rotor blade loads were simulated—the same loads to which blade is exposed under extreme wind-conditions (2% from life time). The applied test loads include simulated steady centrifugal, vibratory flapwise and cordwise (edgewise) bending direction and vibratory torsional pitch motion. The homological fatigue testing program for the blade root involved, conforming to the standards, fatigue testing of one blade [12,44].

5. Fatigue testing

The inboard and root section of the rotor blades is usually tested as a simple cantilever beams. Simulated centrifugal load is applied and an eccentric and a crank arm is used to apply bending loads in. The blades are oriented at an angle to the plane of motion of the eccentric arm, so that combined flapwise and chordwise bending loads are simultaneously applied. The program and the way in which these investigations were carried out on the rotor blades represents a standard practice followed by the majority of scientific and research institutions [12,44].

In the course of the rotor blades attachment fatigue testing program, a very robust facility frame made of steel U and L-profiles tied together with screws was used (Figs. 9–12).

The applied test loads include simulated steady centrifugal, vibratory chordwise bending, vibratory flapwise bending, and vibratory torsional pitch motion. The cyclic load consists of flapping and lagging loads with simultaneous application of the centrifugal force.

Facility test frame used in the wind turbine rotor blades fatigue testing was composed of several basic modules: facility to which rotor blade was attached and fixed, the excitation group and modules for centrifugal force simulations (Figs. 9–12).

For verify the blade's ability to withstand the operating loads for a full design life, 30 year life $> 5 \times 10^8$ cycles applied with accelerated load history from 1 to 10 million cycles (approximately 2% from life time), the standard IEC-61400-23 and IEC WT01 is required. The load applied on one or two axes (flapwise and edgewise direction) and the load methods vary among laboratories.
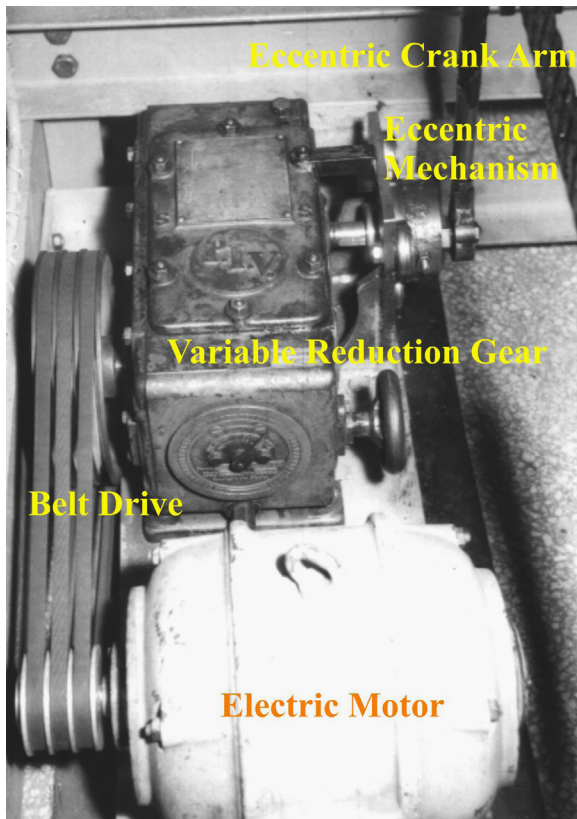
Fig. 11. The excitation group.

Fig. 12. The excitation arm.

The blade attachment module enabled the rotor blades to be fixed into the facility frame and provided an attachment link between the rotor blade and the facility frame, thus enabling the blade adjustments according to the angle of excitation force. The link was formed by two plates and a double tapered spindle. The front plate had the angle of excitation force graduation and the front nut enabled the blade to be securely fixed. The back plate and the nut completely secured the link from being unscrewed. Additional means used to prevent any likely loosening was a slotted bar with the inverted slider-crank mechanism placed at the area of attachment.

The excitation group consisted of an electric motor with a rating of 2.2 kW and rotation speed of 1420 rpm, a belt drive with transmission ratio of 1:3, variable speed drive (variable reduction gear), with a transmission ratio 1–3.25, eccentric mechanism with

an adjustable eccentricity of 0–25 mm and an eccentric crank arm with bonded strain gages for selection excitation (Fig. 11).

The excitation arm is with strain gages and generation of the static load i.e. the centrifugal force, the section that transmitted the force to the blade root section and the blade root attachment fitting at which the centrifugal force was applied at one end and at the same time the excitation force at the other end. A hydraulic servo-controlled actuator composed of a hydraulic cylinder, distribution system with oil lines and a pump with a servomotor and a control manometer was used as the centrifugal force generator. Its maximum force was 40,000 daN. Thanks to this system the basic functioning of the facility frame became automatic (Fig. 10).

In the course of those researches the behavior of the blades was permanently and closely followed. No damages or delamination of the structures i.e. no changes were observed in the course of the testing itself. When the fatigue testing program was completed on the blades, further detailed check-ups and controls in respect to the deformation and degradation of geometrical shape of the blades and delamination were carried out.

On that occasion, no changes were observed on the blades. Strain gauges, (i.e. flat electrical resistors which are glued onto the surface of the rotor blades tested), are used to measure very accurately the bending and stretching of the rotor blades. Infrared cameras are used to reveal local build-up of heat in the blade. This may either indicate an area with structural dampening i.e. an area where the blade designer has deliberately laid out fibres which convert the bending energy into heat in order to stabilize the blade, or it may indicate an area of delamination or an area which is moving toward the breaking point for the fibres. Nondestructive testing (NDT) and inspection (NDI) techniques (reports), such as: (1) acoustic emission, (2) ultrasonic and (3) infrared thermography were successfully applied in the past to detect and locate damage.

6. Vibratory testing

The aim of the wind turbine rotor blade vibratory testing program was to determine the blade major aeroelastic properties. The program included determination of the natural oscillation modes and the structure's natural frequency and also valuation of blade structural damping [14,44].

The main components of the test facility and testing equipment used during the researches consisted of two functionally connected sections: excitation apparatus and response-detection equipment (Fig. 13).

The excitation apparatus consisted of a pulse generator, a signal amplifier, a digital timer/frequency counter, a vibration exciter
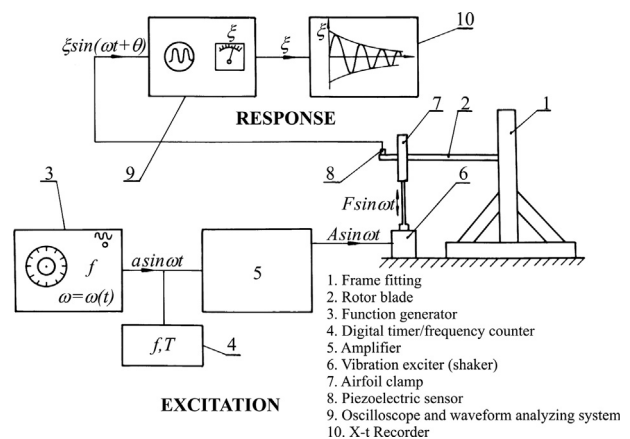

Fig. 13. Employed equipment in vibratory testing.

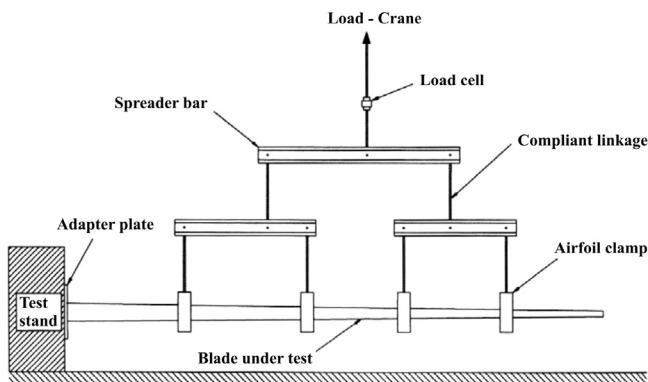**Fig. 14.** Load-introduction airfoil clamp in static testing.

Fig. 15. The loads applied with crane in static testing.

(shaker) and an airfoil clamp for force introduction. The response-detection equipment included: piezoelectric accelerometers, an oscilloscope, a waveform analyzing system, and a multichannel $X-t$ recorder.

In the experiment, a pulse generator, with a sinusoidal excitation function and with a precise adjusting of frequency set-point value in a range from 0.01 to 10,000 Hz, was used. A digital frequency counter was used for precisely read-out the excitation frequency. The exciter was electrodynamic one that is considered to be the most suitable for conducting a harmonic analysis and this type of experiment. The link between the exciter and the rotor blade was formed of an aluminium alloy pipe with an adjustable length and by use of a panel airfoil clamp that was shaped to fit the blade local cross-section at the location of application of excitation. For displacement measurements at the blade selected points, the piezoelectric sensors were used. The special cement was used to intimately stick the pick-up to the surface of blade.

In these researches, as a first step, a harmonic analysis for the blade was performed. After determining the frequencies for the first-four harmonic's natural (resonant) modes of oscillations, displacement vectors for the first-four oscillation modes were measured.

Rotor blade structural damping was determined from the amplitude reduction of free vibration. The blades were excited to vibrate with the first (resonant) oscillation mode with continuously decreasing amplitude due to damping effects.

The logarithmic decrement of the free vibrations was utilized to characterize the structural damping diagram. Its value was determined as:

$$\delta = \frac{1}{n} \ln \frac{x_k}{x_{k+n}} \tag{1}$$

where $n = 10$ is the number of observed oscillations, x_k is observed initial amplitude in the time interval, whereas the corresponding average value of amplitude is:

$$x_m = \frac{1}{2}(x_k + x_{k+n}) \tag{2}$$

Q-factor is also usually used to define the structural damping and gives relative energy (E) reduce in successive oscillations. Q-factor is defined as:

$$Q = \frac{E_1}{E_1 - E_2} \approx \frac{1}{2\delta} \tag{3}$$

where $E_1 - E_2$ is the relative energy reduction in successive oscillations (the energy dissipation in successive oscillations).

7. Static testing

To fit the blade model, a robust facility frame made of steel L and U-profiles was employed. For load application, i.e. for force and torque, an airfoil clamp and a system of wheels and cables mounted on a special frame made of steel profiles were used (Fig. 14). For displacement measurement, comparators with an accuracy of 0.01 mm were used.

To determine the blade torsional stiffness, one needs to define the required torsional moment in the ruling cross-section that would cause torsion of one radian relative to the blade root cross-section.

At torsional testing a low-intensity torque M was applied to the blade by means of the airfoil clam in order to preserve linearity. Blade leading/trailing edge measuring displacements were measured with comparators. Based on the measurements, torsional angles Θ at selected blade cross-sections along its span were calculated. The torsional stiffness was calculated as:

$$m_\Theta = \frac{dM}{d\Theta}[\text{daN mrad}^{-1}] \tag{4}$$

Flexional rotor blade stiffness can be determined from the expression:

$$m_\delta = \frac{Fl^2}{f}[\text{daN mrad}^{-1}] \tag{5}$$

where F is applied force, l is distance between the applied force and the blade fitting point; f is deflection of the elastic axis. The measuring point locations along the blade span were the same as those for the case of torsional testing. Based on these measurements, position and deflection of the blade elastic axis were determined.

Based on the deflection measurement at the leading/trailing blade of the edge's selected cross-sections, the elastic axis deflection was calculated. Consequently, the calculated values of the

elastic axis deflections were utilized to calculate the flexional stiffness for the blade.

The rotor blades are also tested for strength (and thus their ability to withstand extreme loads) by being bent once with a very large force—the ultimate strength static testing. This test is made after the blades are subjected to fatigue testing, in order to verify the strength for a blade which has been in operation for a substantial amount of time. To test the buckling stability verification and failure beyond limit load, the loads were applied with cranes and actuators (Fig. 15).

8. Conclusion

Wind turbine blades are increasingly changing in terms of size and complexity, becoming larger and more complex. Their construction includes a wide variety of materials and manufacturing techniques. To meet the safety requirements of the internationally accepted IEC WT-01 certification scheme, a detailed guidance and interpretation throughout the blade development program is provided by the new blade rules.

Modern wind turbine design involves extensive use, especially of composite materials, and increasing turbine size and structural optimization will entail increased complexity of structural substantiation. In order to manage this, the experience from the aerospace composites industry should be employed along with a recommended widely accepted building block approach to composite structural substantiation based on iterative testing and analysis. This way, confidence in the final design will be achieved.

The IEC standards (Table 1) provide detailed guidance, requirements and supplementary standard interpretation throughout the blade development program, consolidating a huge amount of international experience present in industry and providing a basis for the blade designs in the future.

Acknowledgment

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